Understanding the Behaviour of Laser-Produced Tin Plasmas by Time-Resolved Spectroscopy and Simulation of Their Spectra

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1. Introduction

The strong unresolved-transition arrays (UTA) in a laser-produced plasma (LPP) of tin (Sn) centred near 13.5 nm (fig. 1) offers a promising source of extreme EUV radiation for the next generation of lithography in semiconductor industries. Therefore better understanding of the tin plasma behaviour over time is one of the keys to successfully producing the radiation source.

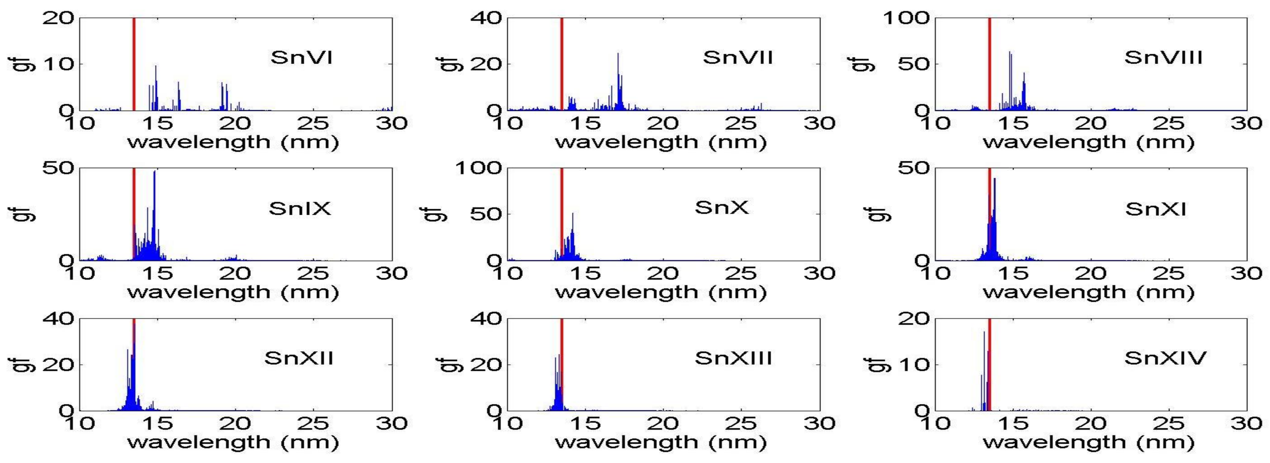

Figure 1: *Tin UTA intensity versus wavelength calculated by Cowan suite of code [1].*

2. Experimental set up

The 1064 nm, 7 ns FWHM output from a Nd:YAG laser operating at 10 Hz is focussed on solid targets of tin housed in a stainless steel vacuum chamber (fig. 2). The chamber is pumped to a pressure of 1.6 x 10^{-6} Torr and coupled to an ISAN grazing incidence spectrograph [2]. The ISAN spectrograph covers the range from 10 to 30 nm. A 3 mm thick slab of tin was translated by actuators to present a fresh surface to the laser after a small number of shots to avoid errors associated with laser drilling. The laser itself was focussed onto the target using a 76.9 mm focal length plano-convex lens.

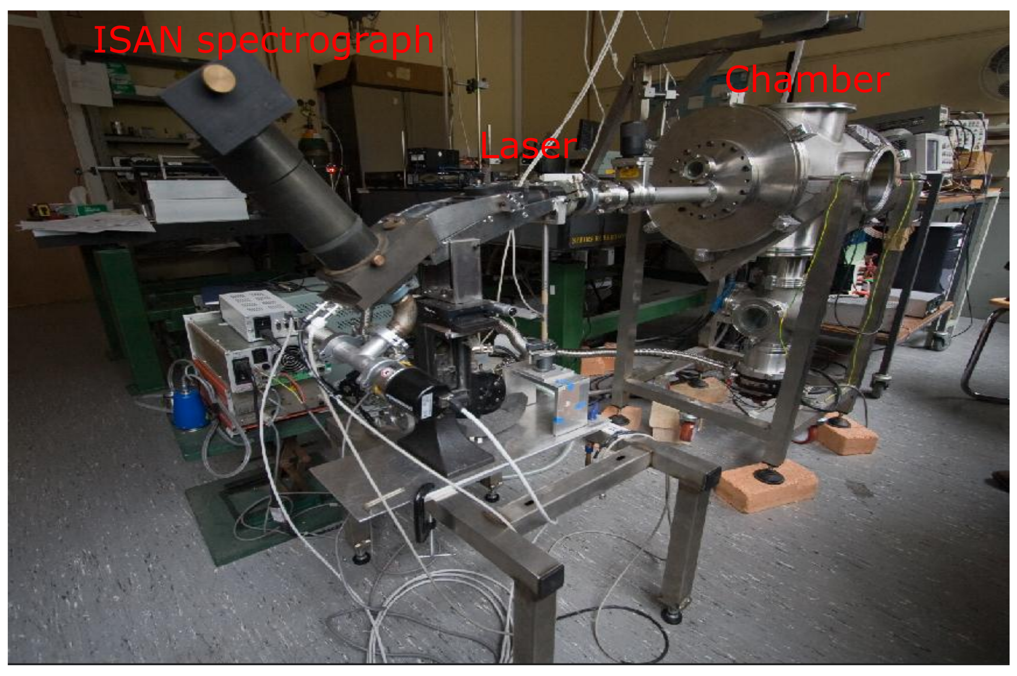

Figure 2: *Experimental set up used in this investigation showing the main chamber and ISAN spectrograph.*

The temporal evolution of the plasma was captured by a gated MCP and a phosphor screen at the output of the spectrograph. The system was capable of 10 ns gate width when triggered by the control pulse. The images on the phosphor screen were captured by a digital camera. Calibration of the wavelength plane was achieved by capturing well documented aluminium spectra (fig 3(a)). An example of an EUV spectrum from a LPP of tin recorded by the spectrograph camera is displayed in fig. 3(b).

3. Results

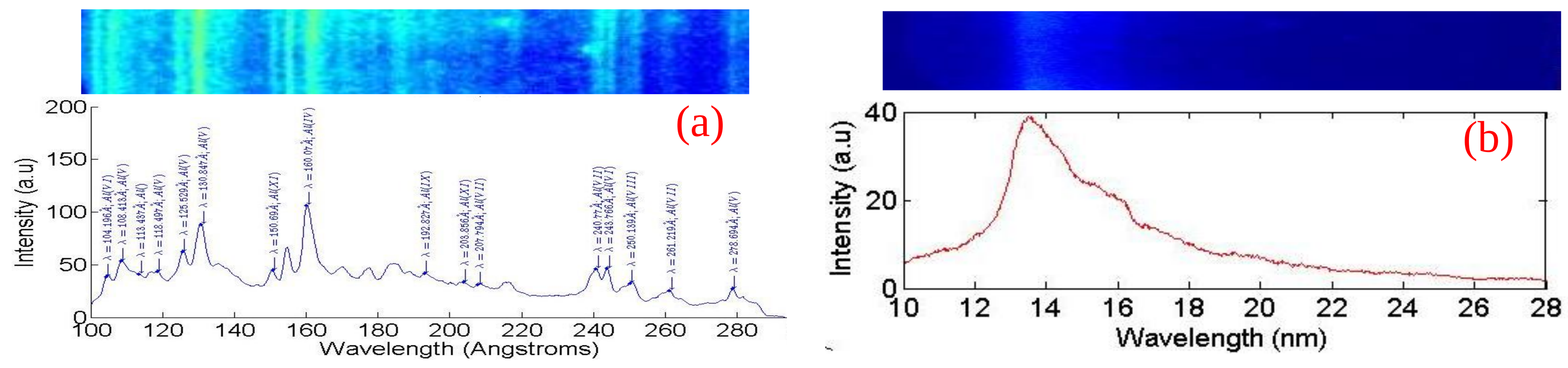

Figure 3: (a) *Aluminium spectrum used as a reference spectrum in the experiments, and (b) Tin spectrum recorded by ISAN spectrograph.*

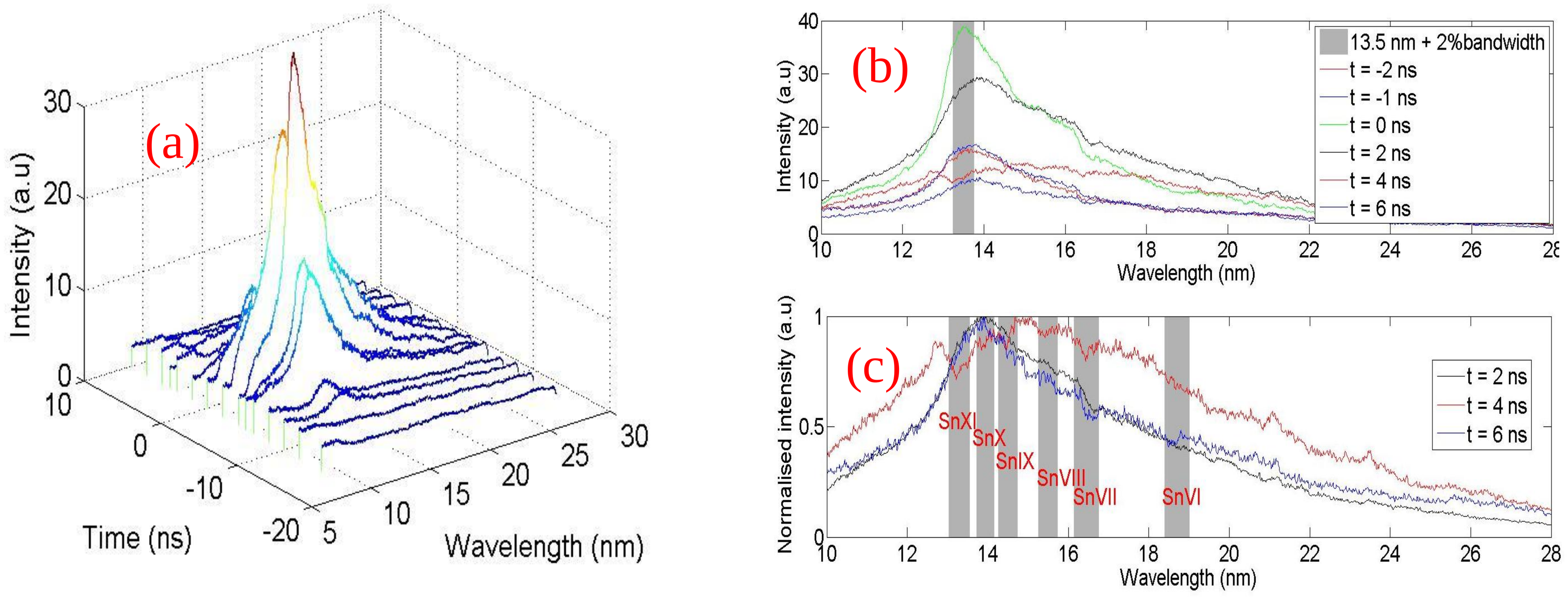

Figure 4: *Sn spectra gated for 10 ns window as a function of time (a) relative to the incident laser (b) relative to the EUV peak (c) relative to the EUV peak during the EUV emission collapse showing self-absorption features due to SnVI to SnXI.*

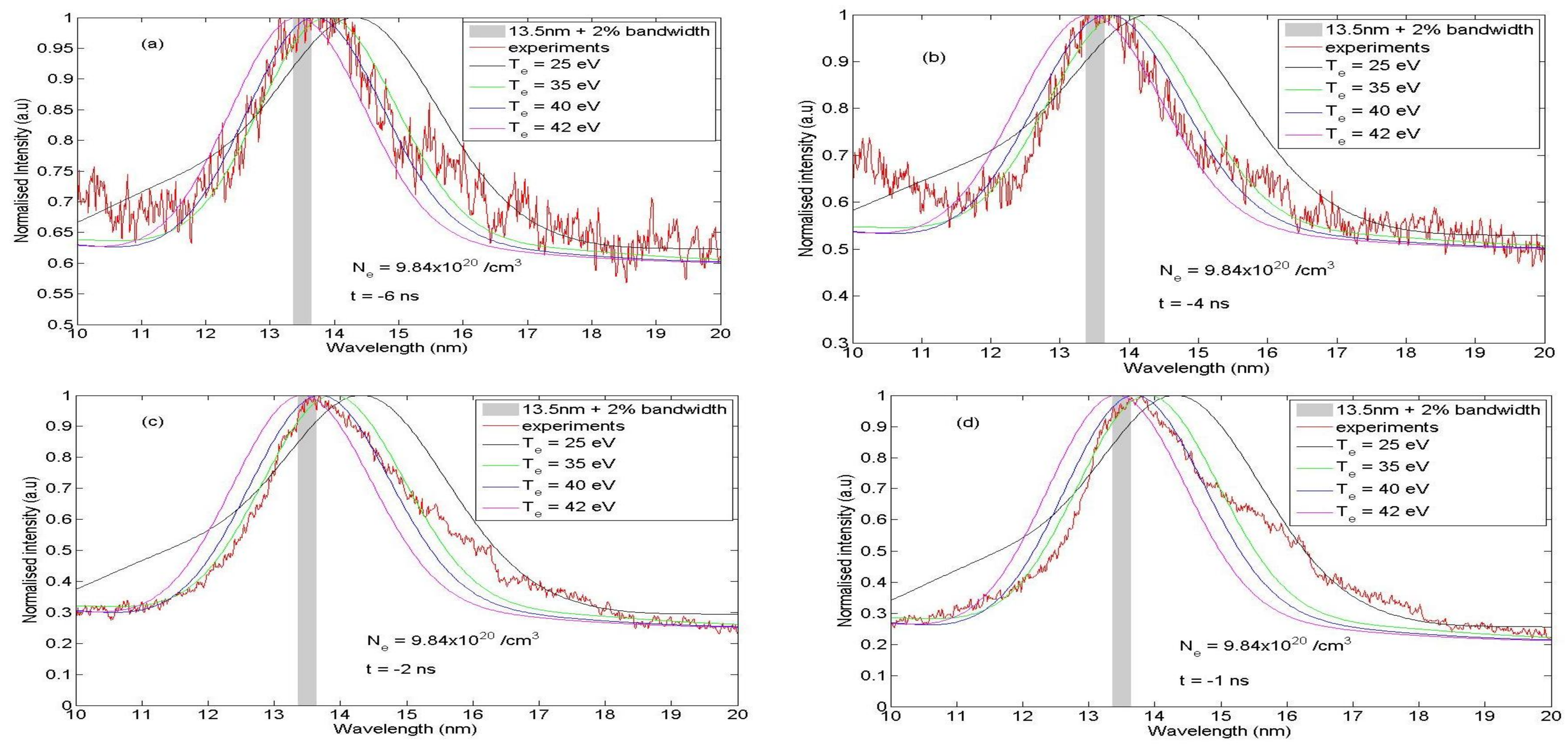

Figure 5: *Comparison of simulated and experimental results for early stages of EUV emission at different times relative to the EUV peak (a) t = -6 ns (b) t = -4 ns (c) t = -2 ns (d) t = -1 ns.*

4. Discussion

The experimental results (fig. 4(a)) show strong EUV emission shortly after the beginning of the laser pulse. The UTA in-band intensity is found to increase over time while the brightest spectrum is observed around the peak of the laser pulse. There is no significant change in the shape of the UTA at the early stages of emission which means that the tin ions contributing are the same at all times before the UTA collapses. However the spectra broaden toward longer wavelengths as the plasma cools down (fig. 4(b)) which indicates that lower ion stages contribute. This trend gives rise to the self-absorption features near the end of the plasma which, based on the theoretical calculations, are due to SnVII – SnXI (fig. 4(c)). The UTA duration, which is determined from the integrated emission over time is found to be ~7 ns. This behaviour closely matches the laser pulse and also agrees with our previous investigation [2]. Using the collisional-radiative (CR), steady state model of Colombant and Tonon it is found that the electron temperatures in the early stages of the EUV emission (t = -6 ns to t = -1 ns relative to the EUV peak) are theoretically estimated to be between 35 – 40 eV (fig. 5(a-d)).

5. Conclusion

The development and collapse of the tin unresolved-transition array (UTA) responsible for the peak EUV emission follow the temporal behaviour of the laser pulse. In the early stages of the EUV emission, the electron temperatures are theoretically estimated to be between 35 – 40 eV. Self-absorption features at longer wavelengths are observed particularly during plasma cooling and arise from lower ion stages ranging from SnVII to SnXI.

Future work

1. Time resolved-spectroscopy of tin plasmas for different time windows/gates.
2. Spatial and angular emission spectroscopy as well as spatial confinement to enhance CE.

References

[1] R. D. Cowan, "The theory of atomic structure and spectra". University of California Press (1981).
[2] T. McCormack, E. Scally, and I. Kambali. "Time-Resolved Studies of Laser-Produced Plasmas of Tin", San Jose: Proceedings of SPIE (2010) 7636-118.
[3] S. S. Harilal, B. O'Shay, and M. S. Tillack. "Spectroscopic characterization of laser-produced tin plasma". Applied Physics 98: p. 013306 (2005).

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